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Determinations of $|V_{ub}|$ from Inclusive Semileptonic B Decays with Reduced Model Dependence

B. Aubert,¹ R. Barate,¹ D. Boutigny,¹ F. Couderc,¹ Y. Karyotakis,¹ J. P. Lees,¹ V. Poireau,¹ V. Tisserand,¹ A. Zghiche,¹ E. Grauges,² A. Palano,³ M. Pappagallo,³ A. Pompili,³ J. C. Chen,⁴ N. D. Qi,⁴ G. Rong,⁴ P. Wang,⁴ Y. S. Zhu,⁴ G. Eigen,⁵ I. Ofte,⁵ B. Stugu,⁵ G. S. Abrams,⁶ M. Battaglia,⁶ D. S. Best,⁶ D. N. Brown,⁶ J. Button-Shafer,⁶ R. N. Cahn,⁶ E. Charles,⁶ C. T. Day,⁶ M. S. Gill,⁶ A. V. Gritsan,^{6,*} Y. Groysman,⁶ R. G. Jacobsen,⁶ R. W. Kadel,⁶ J. A. Kadyk,⁶ L. T. Kerth,⁶ Yu. G. Kolomensky,⁶ G. Kukartsev,⁶ G. Lynch,⁶ L. M. Mir,⁶ P. J. Oddone,⁶ T. J. Orimoto,⁶ M. Pripstein,⁶ N. A. Roe,⁶ M. T. Ronan,⁶ W. A. Wenzel,⁶ M. Barrett,⁷ K. E. Ford,⁷ T. J. Harrison,⁷ A. J. Hart,⁷ C. M. Hawkes,⁷ S. E. Morgan,⁷ A. T. Watson,⁷ M. Fritsch,⁸ K. Goetzen,⁸ T. Held,⁸ H. Koch,⁸ B. Lewandowski,⁸ M. Pelizaeus,⁸ K. Peters,⁸ T. Schroeder,⁸ M. Steinke,⁸ J. T. Boyd,⁹ J. P. Burke,⁹ W. N. Cottingham,⁹ D. Walker,⁹ T. Cuhadar-Donszelmann,¹⁰ B. G. Fulsom,¹⁰ C. Hearty,¹⁰ N. S. Knecht,¹⁰ T. S. Mattison,¹⁰ J. A. McKenna,¹⁰ A. Khan,¹¹ P. Kyberd,¹¹ M. Saleem,¹¹ L. Teodorescu,¹¹ A. E. Blinov,¹² V. E. Blinov,¹² A. D. Bukin,¹² V. P. Druzhinin,¹² V. B. Golubev,¹² E. A. Kravchenko,¹² A. P. Onuchin,¹² S. I. Serednyakov,¹² Yu. I. Skovpen,¹² E. P. Solodov,¹² A. N. Yushkov,¹² M. Bondioli,¹³ M. Bruinsma,¹³ M. Chao,¹³ S. Curry,¹³ I. Eschrich,¹³ D. Kirkby,¹³ A. J. Lankford,¹³ P. Lund,¹³ M. Mandelkern,¹³ R. K. Mommsen,¹³ W. Roethel,¹³ D. P. Stoker,¹³ S. Abachi,¹⁴ C. Buchanan,¹⁴ S. D. Foulkes,¹⁵ J. W. Gary,¹⁵ O. Long,¹⁵ B. C. Shen,¹⁵ K. Wang,¹⁵ L. Zhang,¹⁵ D. del Re,¹⁶ H. K. Hadavand,¹⁶ E. J. Hill,¹⁶ D. B. MacFarlane,¹⁶ H. P. Paar,¹⁶ S. Rahatlou,¹⁶ V. Sharma,¹⁶ J. W. Berryhill,¹⁷ C. Campagnari,¹⁷ A. Cunha,¹⁷ B. Dahmes,¹⁷ T. M. Hong,¹⁷ M. A. Mazur,¹⁷ J. D. Richman,¹⁷ T. W. Beck,¹⁸ A. M. Eisner,¹⁸ C. J. Flacco,¹⁸ C. A. Heusch,¹⁸ J. Kroseberg,¹⁸ W. S. Lockman,¹⁸ G. Nesom,¹⁸ T. Schalk,¹⁸ B. A. Schumm,¹⁸ A. Seiden,¹⁸ P. Spradlin,¹⁸ D. C. Williams,¹⁸ M. G. Wilson,¹⁸ J. Albert,¹⁹ E. Chen,¹⁹ G. P. Dubois-Felsmann,¹⁹ A. Dvoretzskii,¹⁹ D. G. Hitlin,¹⁹ J. S. Minamora,¹⁹ I. Narsky,¹⁹ T. Piatenko,¹⁹ F. C. Porter,¹⁹ A. Ryd,¹⁹ A. Samuel,¹⁹ R. Andreassen,²⁰ G. Mancinelli,²⁰ B. T. Meadows,²⁰ M. D. Sokoloff,²⁰ F. Blanc,²¹ P. C. Bloom,²¹ S. Chen,²¹ W. T. Ford,²¹ J. F. Hirschauer,²¹ A. Kreisel,²¹ U. Nauenberg,²¹ A. Olivas,²¹ W. O. Ruddick,²¹ J. G. Smith,²¹ K. A. Ulmer,²¹ S. R. Wagner,²¹ J. Zhang,²¹ A. Chen,²² E. A. Eckhart,²² A. Soffer,²² W. H. Toki,²² R. J. Wilson,²² F. Winklmeier,²² Q. Zeng,²² D. D. Altenburg,²³ E. Feltresi,²³ A. Hauke,²³ B. Spaan,²³ T. Brandt,²⁴ M. Dickopp,²⁴ V. Klose,²⁴ H. M. Lacker,²⁴ R. Nogowski,²⁴ S. Otto,²⁴ A. Petzold,²⁴ J. Schubert,²⁴ K. R. Schubert,²⁴ R. Schwierz,²⁴ J. E. Sundermann,²⁴ D. Bernard,²⁵ G. R. Bonneaud,²⁵ P. Grenier,^{25,†} E. Latour,²⁵ S. Schrenk,²⁵ Ch. Thiebaux,²⁵ G. Vasileiadis,²⁵ M. Verderi,²⁵ D. J. Bard,²⁶ P. J. Clark,²⁶ W. Gradl,²⁶ F. Muheim,²⁶ S. Playfer,²⁶ Y. Xie,²⁶ M. Andreotti,²⁷ D. Bettoni,²⁷ C. Bozzi,²⁷ R. Calabrese,²⁷ G. Cibinetto,²⁷ E. Luppi,²⁷ M. Negrini,²⁷ L. Piemontese,²⁷ F. Anulli,²⁸ R. Baldini-Ferroli,²⁸ A. Calcaterra,²⁸ R. de Sangro,²⁸ G. Finocchiaro,²⁸ P. Patteri,²⁸ I. M. Peruzzi,^{28,‡} M. Piccolo,²⁸ A. Zallo,²⁸ A. Buzzo,²⁹ R. Capra,²⁹ R. Contri,²⁹ M. Lo Vetere,²⁹ M. M. Macri,²⁹ M. R. Monge,²⁹ S. Passaggio,²⁹ C. Patrignani,²⁹ E. Robutti,²⁹ A. Santroni,²⁹ S. Tosi,²⁹ G. Brandenburg,³⁰ K. S. Chaisanguanthum,³⁰ M. Morii,³⁰ J. Wu,³⁰ R. S. Dubitzky,³¹ U. Langenegger,^{31,§} J. Marks,³¹ S. Schenk,³¹ U. Uwer,³¹ W. Bhimji,³² D. A. Bowerman,³² P. D. Dauncey,³² U. Egede,³² R. L. Flack,³² J. R. Gaillard,³² J. A. Nash,³² M. B. Nikolich,³² W. Panduro Vazquez,³² X. Chai,³³ M. J. Charles,³³ W. F. Mader,³³ U. Mallik,³³ V. Ziegler,³³ J. Cochran,³⁴ H. B. Crawley,³⁴ L. Dong,³⁴ V. Eyges,³⁴ W. T. Meyer,³⁴ S. Prell,³⁴ E. I. Rosenberg,³⁴ A. E. Rubin,³⁴ J. I. Yi,³⁴ G. Schott,³⁵ N. Arnaud,³⁶ M. Davier,³⁶ X. Giroux,³⁶ G. Grosdidier,³⁶ A. Höcker,³⁶ F. Le Diberder,³⁶ V. Lepeltier,³⁶ A. M. Lutz,³⁶ A. Oyanguren,³⁶ T. C. Petersen,³⁶ S. Pruvot,³⁶ S. Rodier,³⁶ P. Roudeau,³⁶ M. H. Schune,³⁶ A. Stocchi,³⁶ W. F. Wang,³⁶ G. Wormser,³⁶ C. H. Cheng,³⁷ D. J. Lange,³⁷ D. M. Wright,³⁷ A. J. Bevan,³⁸ C. A. Chavez,³⁸ I. J. Forster,³⁸ J. R. Fry,³⁸ E. Gabathuler,³⁸ R. Gamet,³⁸ K. A. George,³⁸ D. E. Hutchcroft,³⁸ R. J. Parry,³⁸ D. J. Payne,³⁸ K. C. Schofield,³⁸ C. Touramanis,³⁸ F. Di Lodovico,³⁹ W. Menges,³⁹ R. Sacco,³⁹ C. L. Brown,⁴⁰ G. Cowan,⁴⁰ H. U. Flaecher,⁴⁰ M. G. Green,⁴⁰ D. A. Hopkins,⁴⁰ P. S. Jackson,⁴⁰ T. R. McMahon,⁴⁰ S. Ricciardi,⁴⁰ F. Salvatore,⁴⁰ D. N. Brown,⁴¹ C. L. Davis,⁴¹ J. Allison,⁴² N. R. Barlow,⁴² R. J. Barlow,⁴² Y. M. Chia,⁴² C. L. Edgar,⁴² M. P. Kelly,⁴² G. D. Lafferty,⁴² M. T. Naisbit,⁴² J. C. Williams,⁴² C. Chen,⁴³ W. D. Hulsbergen,⁴³ A. Jawahery,⁴³ D. Kovalskyi,⁴³ C. K. Lae,⁴³ D. A. Roberts,⁴³ G. Simi,⁴³ G. Blaylock,⁴⁴ C. Dallapiccola,⁴⁴ S. S. Hertzbach,⁴⁴ R. Kofler,⁴⁴ X. Li,⁴⁴ T. B. Moore,⁴⁴ S. Saremi,⁴⁴ H. Staengle,⁴⁴ S. Y. Willocq,⁴⁴ R. Cowan,⁴⁵ K. Koeneke,⁴⁵ G. Sciolla,⁴⁵ S. J. Sekula,⁴⁵ M. Spitznagel,⁴⁵ F. Taylor,⁴⁵ R. K. Yamamoto,⁴⁵ H. Kim,⁴⁶ P. M. Patel,⁴⁶ S. H. Robertson,⁴⁶ A. Lazzaro,⁴⁷ V. Lombardo,⁴⁷ F. F. Palombo,⁴⁷ J. M. Bauer,⁴⁸ L. Cremaldi,⁴⁸ V. Eschenburg,⁴⁸ R. Godang,⁴⁸ R. Kroeger,⁴⁸ J. Reidy,⁴⁸ D. A. Sanders,⁴⁸ D. J. Summers,⁴⁸ H. W. Zhao,⁴⁸ S. Brunet,⁴⁹ D. Côté,⁴⁹ P. Taras,⁴⁹ F. B. Viaud,⁴⁹ H. Nicholson,⁵⁰ N. Cavallo,^{51,||} G. De Nardo,⁵¹ F. Fabozzi,^{51,||} C. Gatto,⁵¹ L. Lista,⁵¹ D. Monorchio,⁵¹ P. Paolucci,⁵¹ D. Piccolo,⁵¹ C. Sciacca,⁵¹ M. Baak,⁵² H. Bulten,⁵² G. Raven,⁵² H. L. Snoek,⁵² L. Wilden,⁵² C. P. Jessop,⁵³ J. M. LoSecco,⁵³ T. Allmendinger,⁵⁴ G. Benelli,⁵⁴ K. K. Gan,⁵⁴ K. Honscheid,⁵⁴ D. Hufnagel,⁵⁴ P. D. Jackson,⁵⁴ H. Kagan,⁵⁴ R. Kass,⁵⁴ T. Pulliam,⁵⁴ A. M. Rahimi,⁵⁴ R. Ter-Antonyan,⁵⁴ Q. K. Wong,⁵⁴ N. L. Blount,⁵⁵

J. Brau,⁵⁵ R. Frey,⁵⁵ O. Igonkina,⁵⁵ M. Lu,⁵⁵ C. T. Potter,⁵⁵ R. Rahmat,⁵⁵ N. B. Sinev,⁵⁵ D. Strom,⁵⁵ J. Strube,⁵⁵ E. Torrence,⁵⁵ F. Galeazzi,⁵⁶ M. Margoni,⁵⁶ M. Morandin,⁵⁶ M. Posocco,⁵⁶ M. Rotondo,⁵⁶ F. Simonetto,⁵⁶ R. Stroili,⁵⁶ C. Voci,⁵⁶ M. Benayoun,⁵⁷ J. Chauveau,⁵⁷ P. David,⁵⁷ L. Del Buono,⁵⁷ Ch. de la Vaissière,⁵⁷ O. Hamon,⁵⁷ B. L. Hartfiel,⁵⁷ M. J. J. John,⁵⁷ Ph. Leruste,⁵⁷ J. Malclès,⁵⁷ J. Ocariz,⁵⁷ L. Roos,⁵⁷ G. Therin,⁵⁷ P. K. Behera,⁵⁸ L. Gladney,⁵⁸ J. Panetta,⁵⁸ M. Biasini,⁵⁹ R. Covarelli,⁵⁹ S. Pacetti,⁵⁹ M. Pioppi,⁵⁹ C. Angelini,⁶⁰ G. Batignani,⁶⁰ S. Bettarini,⁶⁰ F. Bucci,⁶⁰ G. Calderini,⁶⁰ M. Carpinelli,⁶⁰ R. Cenci,⁶⁰ F. Forti,⁶⁰ M. A. Giorgi,⁶⁰ A. Lusiani,⁶⁰ G. Marchiori,⁶⁰ M. Morganti,⁶⁰ N. Neri,⁶⁰ E. Paoloni,⁶⁰ M. Rama,⁶⁰ G. Rizzo,⁶⁰ J. Walsh,⁶⁰ M. Haire,⁶¹ D. Judd,⁶¹ D. E. Wagoner,⁶¹ J. Biesiada,⁶² N. Danielson,⁶² P. Elmer,⁶² Y. P. Lau,⁶² C. Lu,⁶² J. Olsen,⁶² A. J. S. Smith,⁶² A. V. Telnov,⁶² F. Bellini,⁶³ G. Cavoto,⁶³ A. D'Orazio,⁶³ E. Di Marco,⁶³ R. Faccini,⁶³ F. Ferrarotto,⁶³ F. Ferroni,⁶³ M. Gaspero,⁶³ L. Li Gioi,⁶³ M. A. Mazzoni,⁶³ S. Morganti,⁶³ G. Piredda,⁶³ F. Polci,⁶³ F. Safai Tehrani,⁶³ C. Voena,⁶³ H. Schröder,⁶⁴ R. Waldi,⁶⁴ T. Adye,⁶⁵ N. De Groot,⁶⁵ B. Franek,⁶⁵ G. P. Gopal,⁶⁵ E. O. Olaiya,⁶⁵ F. F. Wilson,⁶⁵ R. Aleksan,⁶⁶ S. Emery,⁶⁶ A. Gaidot,⁶⁶ S. F. Ganzhur,⁶⁶ G. Graziani,⁶⁶ G. Hamel de Monchenault,⁶⁶ W. Kozanecki,⁶⁶ M. Legendre,⁶⁶ B. Mayer,⁶⁶ G. Vasseur,⁶⁶ Ch. Yèche,⁶⁶ M. Zito,⁶⁶ M. V. Purohit,⁶⁷ A. W. Weidemann,⁶⁷ J. R. Wilson,⁶⁷ T. Abe,⁶⁸ M. T. Allen,⁶⁸ D. Aston,⁶⁸ R. Bartoldus,⁶⁸ N. Berger,⁶⁸ A. M. Boyarski,⁶⁸ O. L. Buchmueller,⁶⁸ R. Claus,⁶⁸ J. P. Coleman,⁶⁸ M. R. Convery,⁶⁸ M. Cristinziani,⁶⁸ J. C. Dingfelder,⁶⁸ D. Dong,⁶⁸ J. Dorfan,⁶⁸ D. Dujmic,⁶⁸ W. Dunwoodie,⁶⁸ S. Fan,⁶⁸ R. C. Field,⁶⁸ T. Glanzman,⁶⁸ S. J. Gowdy,⁶⁸ T. Hadig,⁶⁸ V. Halyo,⁶⁸ C. Hast,⁶⁸ T. Hryn'ova,⁶⁸ W. R. Innes,⁶⁸ M. H. Kelsey,⁶⁸ P. Kim,⁶⁸ M. L. Kocian,⁶⁸ D. W. G. S. Leith,⁶⁸ J. Libby,⁶⁸ S. Luitz,⁶⁸ V. Luth,⁶⁸ H. L. Lynch,⁶⁸ H. Marsiske,⁶⁸ R. Messner,⁶⁸ D. R. Muller,⁶⁸ C. P. O'Grady,⁶⁸ V. E. Ozcan,⁶⁸ A. Perazzo,⁶⁸ M. Perl,⁶⁸ B. N. Ratcliff,⁶⁸ A. Roodman,⁶⁸ A. A. Salnikov,⁶⁸ R. H. Schindler,⁶⁸ J. Schwiening,⁶⁸ A. Snyder,⁶⁸ J. Stelzer,⁶⁸ D. Su,⁶⁸ M. K. Sullivan,⁶⁸ K. Suzuki,⁶⁸ S. K. Swain,⁶⁸ J. M. Thompson,⁶⁸ J. Va'vra,⁶⁸ N. van Bakel,⁶⁸ M. Weaver,⁶⁸ A. J. R. Weinstein,⁶⁸ W. J. Wisniewski,⁶⁸ M. Wittgen,⁶⁸ D. H. Wright,⁶⁸ A. K. Yarritu,⁶⁸ K. Yi,⁶⁸ C. C. Young,⁶⁸ P. R. Burchat,⁶⁹ A. J. Edwards,⁶⁹ S. A. Majewski,⁶⁹ B. A. Petersen,⁶⁹ C. Roat,⁶⁹ S. Ahmed,⁷⁰ M. S. Alam,⁷⁰ R. Bula,⁷⁰ J. A. Ernst,⁷⁰ B. Pan,⁷⁰ M. A. Saeed,⁷⁰ F. R. Wappler,⁷⁰ S. B. Zain,⁷⁰ W. Bugg,⁷¹ M. Krishnamurthy,⁷¹ S. M. Spanier,⁷¹ R. Eckmann,⁷² J. L. Ritchie,⁷² A. Satpathy,⁷² R. F. Schwitters,⁷² J. M. Izen,⁷³ I. Kitayama,⁷³ X. C. Lou,⁷³ S. Ye,⁷³ F. Bianchi,⁷⁴ M. Bona,⁷⁴ F. Gallo,⁷⁴ D. Gamba,⁷⁴ M. Bomben,⁷⁵ L. Bosio,⁷⁵ C. Cartaro,⁷⁵ F. Cossutti,⁷⁵ G. Della Ricca,⁷⁵ S. Dittongo,⁷⁵ S. Grancagnolo,⁷⁵ L. Lanceri,⁷⁵ L. Vitale,⁷⁵ V. Azzolini,⁷⁶ F. Martinez-Vidal,⁷⁶ R. S. Panvini,⁷⁷ Sw. Banerjee,⁷⁸ B. Bhuyan,⁷⁸ C. M. Brown,⁷⁸ D. Fortin,⁷⁸ K. Hamano,⁷⁸ R. Kowalewski,⁷⁸ I. M. Nugent,⁷⁸ J. M. Roney,⁷⁸ R. J. Sobie,⁷⁸ J. J. Back,⁷⁹ P. F. Harrison,⁷⁹ T. E. Latham,⁷⁹ G. B. Mohanty,⁷⁹ H. R. Band,⁸⁰ X. Chen,⁸⁰ B. Cheng,⁸⁰ S. Dasu,⁸⁰ M. Datta,⁸⁰ A. M. Eichenbaum,⁸⁰ K. T. Flood,⁸⁰ M. T. Graham,⁸⁰ J. J. Hollar,⁸⁰ J. R. Johnson,⁸⁰ P. E. Kutter,⁸⁰ H. Li,⁸⁰ R. Liu,⁸⁰ B. Mellado,⁸⁰ A. Mihalyi,⁸⁰ A. K. Mohapatra,⁸⁰ Y. Pan,⁸⁰ M. Pierini,⁸⁰ R. Prepost,⁸⁰ P. Tan,⁸⁰ S. L. Wu,⁸⁰ Z. Yu,⁸⁰ and H. Neal⁸¹

(BABAR Collaboration)

¹Laboratoire de Physique des Particules, F-74941 Annecy-le-Vieux, France

²IFAE, Universitat Autònoma de Barcelona, E-08193 Bellaterra, Barcelona, Spain

³Dipartimento di Fisica and INFN, Università di Bari, I-70126 Bari, Italy

⁴Institute of High Energy Physics, Beijing 100039, China

⁵Institute of Physics, University of Bergen, N-5007 Bergen, Norway

⁶Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA

and University of California, Berkeley, California 94720, USA

⁷University of Birmingham, Birmingham, B15 2TT, United Kingdom

⁸Institut für Experimentalphysik I, Ruhr Universität Bochum, D-44780 Bochum, Germany

⁹University of Bristol, Bristol BS8 1TL, United Kingdom

¹⁰University of British Columbia, Vancouver, British Columbia V6T 1Z1, Canada

¹¹Brunel University, Uxbridge, Middlesex UB8 3PH, United Kingdom

¹²Budker Institute of Nuclear Physics, Novosibirsk 630090, Russia

¹³University of California at Irvine, Irvine, California 92697, USA

¹⁴University of California at Los Angeles, Los Angeles, California 90024, USA

¹⁵University of California at Riverside, Riverside, California 92521, USA

¹⁶University of California at San Diego, La Jolla, California 92093, USA

¹⁷University of California at Santa Barbara, Santa Barbara, California 93106, USA

¹⁸Institute for Particle Physics, University of California at Santa Cruz, Santa Cruz, California 95064, USA

¹⁹California Institute of Technology, Pasadena, California 91125, USA

²⁰University of Cincinnati, Cincinnati, Ohio 45221, USA

²¹University of Colorado, Boulder, Colorado 80309, USA

- ²²Colorado State University, Fort Collins, Colorado 80523, USA
²³Institut für Physik, Universität Dortmund, D-44221 Dortmund, Germany
²⁴Institut für Kern- und Teilchenphysik, Technische Universität Dresden, D-01062 Dresden, Germany
²⁵Ecole Polytechnique, LLR, F-91128 Palaiseau, France
²⁶University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom
²⁷Dipartimento di Fisica and INFN, Università di Ferrara, I-44100 Ferrara, Italy
²⁸Laboratori Nazionali di Frascati dell'INFN, I-00044 Frascati, Italy
²⁹Dipartimento di Fisica and INFN, Università di Genova, I-16146 Genova, Italy
³⁰Harvard University, Cambridge, Massachusetts 02138, USA
³¹Physikalisches Institut, Universität Heidelberg, Philosophenweg 12, D-69120 Heidelberg, Germany
³²Imperial College London, London, SW7 2AZ, United Kingdom
³³University of Iowa, Iowa City, Iowa 52242, USA
³⁴Iowa State University, Ames, Iowa 50011-3160, USA
³⁵Institut für Experimentelle Kernphysik, Universität Karlsruhe, D-76021 Karlsruhe, Germany
³⁶Laboratoire de l'Accélérateur Linéaire, F-91898 Orsay, France
³⁷Lawrence Livermore National Laboratory, Livermore, California 94550, USA
³⁸University of Liverpool, Liverpool L69 7ZE, United Kingdom
³⁹Queen Mary, University of London, E1 4NS, United Kingdom
⁴⁰Royal Holloway and Bedford New College, University of London, Egham, Surrey TW20 0EX, United Kingdom
⁴¹University of Louisville, Louisville, Kentucky 40292, USA
⁴²University of Manchester, Manchester M13 9PL, United Kingdom
⁴³University of Maryland, College Park, Maryland 20742, USA
⁴⁴University of Massachusetts, Amherst, Massachusetts 01003, USA
⁴⁵Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA
⁴⁶McGill University, Montréal, Québec H3A 2T8, Canada
⁴⁷Dipartimento di Fisica and INFN, Università di Milano, I-20133 Milano, Italy
⁴⁸University of Mississippi, University, Mississippi 38677, USA
⁴⁹Physique des Particules, Université de Montréal, Montréal, Québec H3C 3J7, Canada
⁵⁰Mount Holyoke College, South Hadley, Massachusetts 01075, USA
⁵¹Dipartimento di Scienze Fisiche and INFN, Università di Napoli Federico II, I-80126, Napoli, Italy
⁵²NIKHEF, National Institute for Nuclear Physics and High Energy Physics, NL-1009 DB Amsterdam, The Netherlands
⁵³University of Notre Dame, Notre Dame, Indiana 46556, USA
⁵⁴Ohio State University, Columbus, Ohio 43210, USA
⁵⁵University of Oregon, Eugene, Oregon 97403, USA
⁵⁶Dipartimento di Fisica and INFN, Università di Padova, I-35131 Padova, Italy
⁵⁷Laboratoire de Physique Nucléaire et de Hautes Energies, Universités Paris VI et VII, F-75252 Paris, France
⁵⁸University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA
⁵⁹Dipartimento di Fisica and INFN, Università di Perugia, I-06100 Perugia, Italy
⁶⁰Dipartimento di Fisica, Scuola Normale Superiore, and INFN, Università di Pisa, I-56127 Pisa, Italy
⁶¹Prairie View A&M University, Prairie View, Texas 77446, USA
⁶²Princeton University, Princeton, New Jersey 08544, USA
⁶³Dipartimento di Fisica and INFN, Università di Roma La Sapienza, I-00185 Roma, Italy
⁶⁴Universität Rostock, D-18051 Rostock, Germany
⁶⁵Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, OX11 0QX, United Kingdom
⁶⁶DSM/Dapnia, CEA/Saclay, F-91191 Gif-sur-Yvette, France
⁶⁷University of South Carolina, Columbia, South Carolina 29208, USA
⁶⁸Stanford Linear Accelerator Center, Stanford, California 94309, USA
⁶⁹Stanford University, Stanford, California 94305-4060, USA
⁷⁰State University of New York, Albany, New York 12222, USA
⁷¹University of Tennessee, Knoxville, Tennessee 37996, USA
⁷²University of Texas at Austin, Austin, Texas 78712, USA
⁷³University of Texas at Dallas, Richardson, Texas 75083, USA
⁷⁴Dipartimento di Fisica Sperimentale and INFN, Università di Torino, I-10125 Torino, Italy
⁷⁵Dipartimento di Fisica and INFN, Università di Trieste, I-34127 Trieste, Italy
⁷⁶IFIC, Universitat de Valencia-CSIC, E-46071 Valencia, Spain
⁷⁷Vanderbilt University, Nashville, Tennessee 37235, USA
⁷⁸University of Victoria, Victoria, British Columbia V8W 3P6, Canada
⁷⁹Department of Physics, University of Warwick, Coventry CV4 7AL, United Kingdom
⁸⁰University of Wisconsin, Madison, Wisconsin 53706, USA
⁸¹Yale University, New Haven, Connecticut 06511, USA

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We report two novel determinations of $|V_{ub}|$ with reduced model dependence, based on measurements of the mass distribution of the hadronic system in semileptonic B decays. Events are selected by fully reconstructing the decay of one B meson and identifying a charged lepton from the decay of the other B meson from $Y(4S) \rightarrow B\bar{B}$ events. In one approach, we combine the inclusive $\bar{B} \rightarrow X_u \ell \bar{\nu}$ rate, integrated up to a maximum hadronic mass $m_X < 1.67 \text{ GeV}/c^2$, with a measurement of the inclusive $B \rightarrow X_s \gamma$ photon energy spectrum. We obtain $|V_{ub}| = (4.43 \pm 0.38_{\text{stat}} \pm 0.25_{\text{syst}} \pm 0.29_{\text{theo}}) \times 10^{-3}$. In another approach we measure the total $\bar{B} \rightarrow X_u \ell \bar{\nu}$ rate over the full phase space and find $|V_{ub}| = (3.84 \pm 0.70_{\text{stat}} \pm 0.30_{\text{syst}} \pm 0.10_{\text{theo}}) \times 10^{-3}$.

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The measurement of the element V_{ub} of the Cabibbo-Kobayashi-Maskawa quark-mixing matrix [1] plays a critical role in testing the consistency of the standard model description of CP violation. The uncertainties in existing measurements [2,3] are dominantly due to uncertainties in the b -quark mass m_b and the modeling of the Fermi motion of the b quark inside the \bar{B} meson [4]. In this Letter, we present two techniques to extract $|V_{ub}|$ from inclusive $\bar{B} \rightarrow X_u \ell \bar{\nu}$ [5] decays where these uncertainties are significantly reduced. Neither method has been previously implemented experimentally.

Leibovich, Low, and Rothstein (LLR) have presented a prescription to extract $|V_{ub}|$ with reduced model dependence from either the lepton energy or the hadronic mass m_X [6]. A technique utilizing weight functions had been proposed previously by Neubert [4]. The calculations of LLR are accurate up to corrections of order α_s^2 and $[\Lambda m_B/(\zeta m_b)]^2$, where ζ is the experimental maximum hadronic mass up to which the $\bar{B} \rightarrow X_u \ell \bar{\nu}$ decay rate is determined and $\Lambda \approx \Lambda_{\text{QCD}}$. This method combines the hadronic mass spectrum, integrated below ζ , with the high-energy end of the measured differential $B \rightarrow X_s \gamma$ photon energy spectrum via the calculations of LLR.

An alternative method [7] to reduce the model dependence is to measure the $\bar{B} \rightarrow X_u \ell \bar{\nu}$ rate over the entire m_X spectrum. Since no extrapolation is necessary to obtain the full rate, systematic uncertainties from m_b and Fermi motion are much reduced. Perturbative corrections are known to order α_s^2 . We extract the $\bar{B} \rightarrow X_u \ell \bar{\nu}$ rate from the hadronic mass spectrum up to $\zeta = 2.5 \text{ GeV}/c^2$ which corresponds to about 96% of the simulated hadronic mass spectrum.

The measurements presented here are based on a sample of $88.9 \times 10^6 B\bar{B}$ pairs collected near the $Y(4S)$ resonance by the BABAR detector [8] at the PEP-II asymmetric-energy e^+e^- storage rings operating at SLAC. The analysis uses $Y(4S) \rightarrow B\bar{B}$ events in which one of the B mesons decays hadronically and is fully reconstructed (B_r) and the other decays semileptonically (\bar{B}_{sl}). To reconstruct a large sample of B mesons, we follow the procedure described in Ref. [2] in which charged and neutral hadrons are combined with an exclusively reconstructed D meson to obtain combinations with an energy consistent with a B meson. While this approach results in a low overall event selection efficiency, it allows for the precise determination of the momentum, charge, and flavor of the B_r candidates.

We use Monte Carlo (MC) simulations of the BABAR detector based on GEANT4 [9] to optimize selection criteria and to determine signal efficiencies and background distributions. Charmless semileptonic $\bar{B} \rightarrow X_u \ell \bar{\nu}$ decays are simulated as a combination of resonant three-body decays ($X_u = \pi, \rho, \omega, \eta, \eta'$) [10], and decays to nonresonant hadronic final states X_u [11] for which the hadronization is performed by JETSET7.4 [12]. The effect of Fermi motion is implemented in the simulation using an exponential function [11] with the parameters $m_b = 4.79 \text{ GeV}/c^2$ and $\lambda_1 = -0.24 \text{ GeV}^2/c^4$ [13]. The simulation of the $\bar{B} \rightarrow X_c \ell \bar{\nu}$ background uses a heavy quark effective theory parameterization of form factors for $\bar{B} \rightarrow D^* \ell \bar{\nu}$ [14] and models for $\bar{B} \rightarrow D \pi \ell \bar{\nu}$, $D^* \pi \ell \bar{\nu}$ [15], and $\bar{B} \rightarrow D \ell \bar{\nu}$, $D^{**} \ell \bar{\nu}$ [10] decays.

Semileptonic \bar{B}_{sl} candidates are identified by the presence of at least one electron or muon with momentum $p_\ell^* > 1 \text{ GeV}/c$ in the \bar{B}_{sl} rest frame. For charged B_r candidates, we require the charge of the lepton to be consistent with a primary decay of a \bar{B}_{sl} . For neutral B_r candidates, both charge-flavor combinations are retained and the average $B^0\text{-}\bar{B}^0$ mixing rate [16] is used to determine the primary lepton yield. Electrons (muons) are identified [17] (Ref. [8]), with a 92% (60–75%) average efficiency and a hadron misidentification rate ranging between 0.05% and 0.1% (1–3%).

The hadronic system X in the $\bar{B} \rightarrow X \ell \bar{\nu}$ decays is reconstructed from charged tracks and energy depositions in the calorimeter that are not associated with the B_r candidate or the identified lepton. The neutrino four-momentum p_ν is estimated from the missing momentum four-vector $p_{\text{miss}} = p_{Y(4S)} - p_{B_r} - p_X - p_\ell$, where all momenta are measured in the laboratory frame and $p_{Y(4S)}$ refers to the $Y(4S)$ momentum.

To select $\bar{B} \rightarrow X_u \ell \bar{\nu}$ candidates we require exactly one lepton with $p_\ell^* > 1 \text{ GeV}/c$ in the event, charge conservation ($Q_X + Q_\ell + Q_{B_r} = 0$), and a missing four-momentum consistent with a neutrino hypothesis, i.e., missing mass consistent with zero ($-1.0 < m_{\text{miss}}^2 < 0.5 \text{ GeV}^2/c^4$), $|p_{\text{miss}}| > 0.3 \text{ GeV}/c$, and $|\cos\theta_{\text{miss}}| < 0.95$, where θ_{miss} is the polar angle of the missing momentum three-vector \mathbf{p}_{miss} . These criteria suppress the majority of $\bar{B} \rightarrow X_c \ell \bar{\nu}$ decays that contain additional neutrinos or an undetected K_L^0 meson. Additionally we reject events with charged or neutral kaons (reconstructed as $K_S^0 \rightarrow \pi^+ \pi^-$ decays) in the decay products of the \bar{B}_{sl} . We suppress $\bar{B} \rightarrow D^* \ell \bar{\nu}$

backgrounds by partial reconstruction of charged and neutral D^* mesons via identification of charged and neutral slow pions. The reconstruction of the mass of the hadronic system is improved by a kinematic fit that imposes four-momentum conservation, the equality of the masses of the two B mesons, and $p_\nu^2 = 0$. The resulting m_X resolution is ~ 250 MeV/ c^2 on average.

The extraction of $|V_{ub}|/|V_{ts}|$ from the selected events starts from the equation [6]

$$\frac{|V_{ub}|}{|V_{ts}|} = \left\{ \frac{6\alpha(1 + H_{\text{mix}}^\gamma)(C_7^{(0)})^2}{\pi[I_0(\zeta) + I_+(\zeta)]} \delta\mathcal{R}_u(\zeta) \right\}^{1/2}, \quad (1)$$

where $\delta\mathcal{R}_u(\zeta)$ is the partial charmless semileptonic decay rate extracted from the number of $\bar{B} \rightarrow X_u \ell \bar{\nu}$ events up to a limit ζ in the m_X spectrum. H_{mix}^γ accounts for interferences between electromagnetic penguin operator O_7 with O_2 and O_8 [18], and $C_7^{(0)}$ is the effective Wilson coefficient. The terms $I_0(\zeta)$ and $I_+(\zeta)$ are determined by multiplying the photon energy spectrum $d\Gamma^\gamma/dE_\gamma$ in $B \rightarrow X_s \gamma$ decays [13] with weight functions [6] and integrating. The weights are zero below a minimum photon energy $E_\gamma^{\text{min}} = m_B/2 - \zeta/4$.

In terms of measurable quantities, $\delta\mathcal{R}_u(\zeta)$ is

$$\delta\mathcal{R}_u(\zeta) = \frac{N_u(\zeta)f(\zeta)\mathcal{B}(\bar{B} \rightarrow X\ell\bar{\nu})}{N_{\text{sl}}\epsilon_u(\zeta)} \frac{\epsilon_\ell^{\text{sl}}}{\epsilon_\ell^u} \frac{\epsilon_{\text{reco}}^{\text{sl}}}{\epsilon_{\text{reco}}^u}. \quad (2)$$

Here, $N_u(\zeta)$ is the number of reconstructed $\bar{B} \rightarrow X_u \ell \bar{\nu}$ events with $m_X < \zeta$, $f(\zeta)$ accounts for migration in and out of the region below ζ due to finite m_X resolution, $\mathcal{B}(\bar{B} \rightarrow X\ell\bar{\nu})$ is the total inclusive semileptonic branching fraction, and $\epsilon_u(\zeta)$ is the efficiency for selecting $\bar{B} \rightarrow X_u \ell \bar{\nu}$ decays once a $\bar{B} \rightarrow X\ell\bar{\nu}$ decay has been identified with a hadronic mass below ζ . N_{sl} is the number of observed fully reconstructed B meson decays with a charged lepton with momentum above 1 GeV/ c , $\epsilon_\ell^{\text{sl}}/\epsilon_\ell^u$ corrects for the difference in the efficiency of the lepton momentum selection for $\bar{B} \rightarrow X\ell\bar{\nu}$ and $\bar{B} \rightarrow X_u \ell \bar{\nu}$ decays, and $\epsilon_{\text{reco}}^{\text{sl}}/\epsilon_{\text{reco}}^u$ accounts for the difference in the efficiency of reconstructing a B_r in events with a $\bar{B} \rightarrow X\ell\bar{\nu}$ and $\bar{B} \rightarrow X_u \ell \bar{\nu}$ decay. By measuring the ratio of $\bar{B} \rightarrow X_u \ell \bar{\nu}$ events to all semileptonic B decays many systematic uncertainties cancel out.

We derive $N_u(\zeta)$ from the m_X distribution with a binned χ^2 fit to four components: data, $\bar{B} \rightarrow X_u \ell \bar{\nu}$ signal MC simulations, $\bar{B} \rightarrow X_c \ell \bar{\nu}$ background MC simulations, and a small MC background from other sources (misidentified leptons, $\bar{B} \rightarrow X\tau\bar{\nu}$, and charm decays), fixed relative to the $\bar{B} \rightarrow X_c \ell \bar{\nu}$ component. $N_u(\zeta)$ is determined after the subtraction of the fitted background contributions. For all four contributions, the combinatorial background is determined, separately in each bin of the m_X distribution, with unbinned maximum likelihood fits to distributions of the beam energy-substituted mass $m_{\text{ES}} = \sqrt{s/4 - \mathbf{p}_B^2}$ of the B_r

candidate, where \sqrt{s} is the e^+e^- center-of-mass energy. The m_{ES} fit uses an empirical description of the combinatorial background shape [19] with a signal shape [20] peaking at the B meson mass. The combinatorial background varies from 5% (low m_X bins) to 25% (high m_X bins). The fitted m_X distributions are shown in Fig. 1(a) before and in Fig. 1(b) after subtraction of backgrounds. The m_X bins are 300 MeV/ c^2 wide except that one bin is widened such that its upper edge is at ζ .

We extract $N_{\text{sl}} = (3.253 \pm 0.024) \times 10^4$ from an unbinned maximum likelihood fit to the m_{ES} distribution of all events with $p_\ell^* > 1$ GeV/ c . The efficiency corrections $\epsilon_\ell^{\text{sl}}/\epsilon_\ell^u = 0.82 \pm 0.02_{\text{stat}}$, as well as $\epsilon_u(\zeta)$ and $f(\zeta)$ (see Table I) are derived from simulations, where we also find $\epsilon_{\text{reco}}^{\text{sl}}/\epsilon_{\text{reco}}^u$ in agreement with one, assigning a 3% uncertainty.

We study three categories of systematic uncertainties in the determination of $|V_{ub}|$: uncertainties in the signal extraction, the simulation of physics processes, and the theoretical description. The quoted uncertainties have been determined for a value of $\zeta = 1.67$ GeV/ c^2 where the total uncertainty on $|V_{ub}|$ is found to be minimal.

Experimental uncertainties in the signal extraction arise from imperfect description of data by the detector simulation. We assign 0.5% (0.5%, 0.8%) for the particle identification of electrons (μ , K^\pm), 0.7% for the reconstruction efficiency of charged particles, and 0.8% for the resolution and reconstruction efficiency of neutral particles. An additional 0.9% uncertainty is due to imperfect simulation of K_L^0 interactions. By changing the function describing the signal shape in m_{ES} to a Gaussian function and switching from an unbinned to a binned fit method we derive an uncertainty of 2.2%. An uncertainty of 0.8% is determined by letting the contribution from other sources (see above) to the m_X spectrum float freely in the minimum- χ^2 fit. The uncertainties on the inclusive $B \rightarrow X_s \gamma$ photon energy

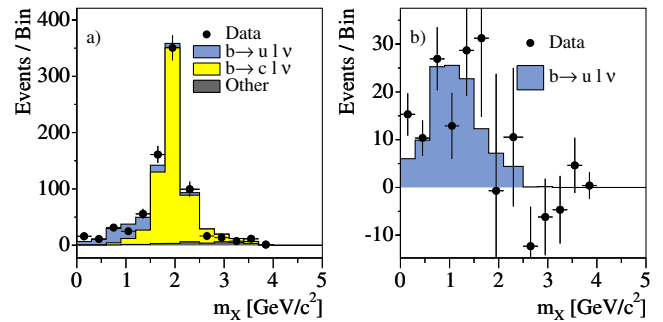


FIG. 1 (color online). The m_X distributions (without combinatorial backgrounds) for $\bar{B} \rightarrow X\ell\bar{\nu}$ candidates: (a) data (points) and fit components after the minimum- χ^2 fit, and (b) data and signal MC simulations after subtraction of the $\bar{B} \rightarrow X_c \ell \bar{\nu}$ and other backgrounds. The upper edge of the eighth bin is chosen to be at $m_X = 2.5$ GeV/ c^2 . This fit result, with $\chi^2 = 10.2$ for 11 degrees of freedom, is used to extract the number of signal events below 2.5 GeV/ c^2 .

TABLE I. Quantities in Eq. (2) that depend on ζ and their statistical uncertainties. The LLR (full rate) technique is given in the first (second) column.

ζ	1.67 GeV/c ²	2.50 GeV/c ²
f	1.010 ± 0.005	0.998 ± 0.002
N_u	120 ± 17	135 ± 45
ε_u	0.231 ± 0.005	0.231 ± 0.004
$\delta\mathcal{R}_u \times 10^3$	1.43 ± 0.21	1.59 ± 0.53

spectrum are propagated including the full correlation matrix between the individual bins.

The second category of systematic uncertainties arises from imperfections in the composition and dynamics of decays in the simulation, both in signal and background. The uncertainties in the branching fractions of $B \rightarrow D^{(*)}l\bar{\nu}X$ decays [16] contribute 0.7%. The uncertainties in the form factors in $B \rightarrow D^*l\bar{\nu}$ decays [14] introduce a 0.3% uncertainty. Branching fractions of D -meson decay channels [16] contribute 0.2%. The relative contribution of the nonresonant final states has been varied by 20% resulting in an uncertainty of 0.5%. The branching fractions of the resonant final states have been varied by $\pm 30\%$ (π, ρ), $\pm 40\%$ (ω), and $\pm 100\%$ (η and η' simultaneously) resulting in an uncertainty of 1.0%. An uncertainty of 0.7% due to imperfect description of hadronization is determined from the change observed when we saturate the spectrum with the nonresonant component alone. We derive a 1.3% uncertainty due to the imperfect modeling of the $K\bar{K}$ content in the X_u system by varying the fraction of decays to $s\bar{s}$ pairs by 30% for the nonresonant contribution [21]. Even though the extraction of $|V_{ub}|$ does not explicitly depend on a model for Fermi motion, there is still a residual dependency via the simulation of signal events. By varying the Fermi motion parameters m_b and λ_1 within their respective uncertainties, taking correlations into account [13], we derive an uncertainty of 3.5%.

We calculate theoretical uncertainties in the weighting technique by varying the input parameters and repeating the weighting procedure including the calculation of all

TABLE II. Summary of results and uncertainties on $|V_{ub}|$ for both approaches. The LLR (full rate) technique is given in the first (second) column.

ζ [GeV/c ²]	1.67	2.5
$ V_{ub} \times 10^3$	4.43	3.84
$\bar{B} \rightarrow X_u \ell \bar{\nu}$ stat.	7.7%	18.2%
Experimental syst.	3.3%	3.6%
Background model	1.0%	3.8%
Signal model	3.9%	5.6%
Theoretical	6.2%	2.6%
$B \rightarrow X_s \gamma$ (stat., syst.)	3.5%, 2.0%	...
$ V_{cb} $ (exp., theo.)	1.0%, 1.7%	...

variables: H_{mix}^γ , α_s , and Wilson-coefficients. We vary α between $\alpha(m_b)$ and $\alpha(m_W)$ with a central value of $1/130.3$ and find an uncertainty of less than 1%. For perturbative effects, an uncertainty of 2.9% is derived by varying the renormalization scale μ between $m_b/2$ and $2m_b$. Nonperturbative effects are expected to be of the order $[\Lambda m_B/(\zeta m_b)]^2$, where $\Lambda = 500 \text{ MeV}/c^2$ [22], resulting in an uncertainty of 5.4%. Theoretical uncertainties in the measurement via the full rate are taken from Ref. [23] to be 1.2% (QCD) and 2.2% (HQE). Table II provides a summary of the uncertainties for $\zeta = 1.67 \text{ GeV}/c^2$ and for $\zeta = 2.5 \text{ GeV}/c^2$.

Finally, we present two different determinations of $|V_{ub}|$. First, using the weighting technique with the photon energy spectrum in $B \rightarrow X_s \gamma$ decays from Ref. [13], the hadronic mass spectrum up to a value of $\zeta = 1.67 \text{ GeV}/c^2$, we find $|V_{ub}|/|V_{ts}| = 0.107 \pm 0.009_{\text{stat}} \pm 0.006_{\text{syst}} \pm 0.007_{\text{theo}}$. If we assume the Cabibbo-Kobayashi-Maskawa matrix is unitary then $|V_{ts}| = |V_{cb}| \times [1 \pm \mathcal{O}(1\%)]$ and, taking $|V_{cb}|$ from Ref. [24], we derive

$$|V_{ub}| = (4.43 \pm 0.38 \pm 0.25 \pm 0.29) \times 10^{-3},$$

where the first error is the statistical uncertainty from $\bar{B} \rightarrow X_u \ell \bar{\nu}$ and from $B \rightarrow X_s \gamma$ added in quadrature, the second (third) is systematic (theoretical). Second, we determine $|V_{ub}|$ from a measurement of the full m_X spectrum, i.e., up to a value of $\zeta = 2.5 \text{ GeV}/c^2$, and find $|V_{ub}| = (3.84 \pm 0.70_{\text{stat}} \pm 0.30_{\text{syst}} \pm 0.10_{\text{theo}}) \times 10^{-3}$, using the average B lifetime of $\tau_B = (1.604 \pm 0.012) \text{ ps}$ [16,25].

The weighting technique is expected to break down at low values of ζ , since only a small fraction of the phase space is used. Figure 2 illustrates the dependence of the result, and its statistical and theoretical uncertainties, on variations of ζ and also compares it with the value of $|V_{ub}|$ determined from the full rate. The weighting technique

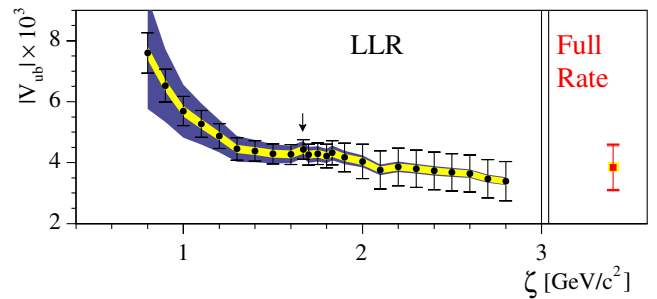


FIG. 2 (color online). $|V_{ub}|$ as a function of ζ with the LLR method (left) and for the determination with the full rate measurement (right). The error bars indicate the statistical uncertainty. They are correlated between the points and get larger for larger ζ due to larger background from $\bar{B} \rightarrow X_c \ell \bar{\nu}$. The total shaded area illustrates the theoretical uncertainty; the inner light shaded (yellow online) area indicates the perturbative share of the uncertainty. The arrow indicates $\zeta = 1.67 \text{ GeV}/c^2$.

appears to be stable down to $\zeta \sim 1.4 \text{ GeV}/c^2$. The current uncertainties on the $B \rightarrow X_s \gamma$ photon energy spectrum limit the sensitivity with which the behavior at high ζ can be probed.

The above results are consistent with previous measurements [2,3] but have substantially smaller uncertainties from m_b and the modeling of Fermi motion. Both techniques are based on theoretical calculations that are distinct from other calculations normally employed to extract $|V_{ub}|$ and, thus, provide a complementary determination of $|V_{ub}|$.

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*Also with the Johns Hopkins University, Baltimore, MD 21218, USA

†Also at Laboratoire de Physique Corpusculaire, Clermont-Ferrand, France

‡Also with Dipartimento di Fisica, Università di Perugia, Perugia, Italy

§Now at Institute for Particle Physics, ETH Zürich, CH-8093 Zürich, Switzerland

||Also with Università della Basilicata, Potenza, Italy

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